UNUSUALLY HIGH RECRUITMENT IN THE SHARK BAY SAUCER SCALLOP (*AMUSIUM BALLOTI*) FISHERY

L.M. JOLL

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From 1983, when the Shark Bay scallop fishery reached full exploitation, to 1990, the largest annual catch had been 731 tonnes (meat weight) in 1988. In 1991 and 1992 catches of 2,532 and 4,144 tonnes, respectively, were taken. The increased catch in 1991 was attained despite total effort being the second lowest on record, while catch per unit effort (CPUE) was the highest on record. Total effort in 1992 increased considerably and was the highest on record, while CPUE was second only to that achieved in 1991. The very high catches and CPUEs were the result of a massive increase in the recruitment of juveniles derived from the 1990 breeding season. Annual stock surveys showed recruitment indices in some areas of Shark Bay up to six times higher than the previous record. Juveniles recruited in 1990 formed the bulk of the fishable stock in 1991, but the available effort in the fishery was unable to take all the fishable stock in 1991 and the 1992 catch was composed mostly of residual animals carried over from the 1991 season. High recruitment into the Shark Bay saucer scallop fishery is usually associated with low mean sea levels (= weak Leeuwin Current) over the winter (spawning) months. A chance association of spawning with an additional hydrological or other environmental event favourable to larval retention or survival may have multiplied the effect of a weak Leeuwin Current.

L.M. Joll, Bernard Bowen Fisheries Research Institute, Western Australian Marine Research Laboratories, P.O. Box 20, North Beach, Western Australia 6020; 9 March 1994.

The fishery for saucer scallops (*Amusium balloti* Bernardi, 1861) in Shark Bay has been fully exploited since 1983; its catch depends on recruitment from the breeding season of the previous year (Joll & Caputi, in press). Surveys of recruit (0+) and residual (1+ and older) scallops at the start of each season showed recruitment from the 1990 breeding season as the highest recorded. As a result of the very high recruitment, the 1991 catch was approximately three times higher than the previous record catch. However, despite the high catch in 1991, there were still large numbers of scallops at the end of the 1991 season. These formed the basis of the 1992 fishery, which took a catch over 50% greater than the record 1991 catch. Joll & Caputi (in press) have shown that these high levels of recruitment are associated with low mean sea levels, which reflect periods of a weak Leeuwin Current. This paper examines the background to the high 1990 recruitment and documents features of the event for use in population dynamics studies.

MATERIALS AND METHODS

Scallops are caught by vessels which are licenced to fish only for scallops (using 25.6m [14fm] headrope length nets of 100mm mesh) and vessels which fish for prawns and scallops (using (29.3m [16fm] nets of 50mm mesh) (Joll,1987,1989a). Catch and effort data are obtained from a voluntary logbook system completed by all vessels in both sectors of the fishery, and catch data are cross-checked with receival records of wholesale buyers. Catch per unit effort (CPUE) data were derived from the catch and effort of the scallop fleet. Effort of prawn/scallop vessels may be directed at either prawns or scallops or a combination of the two. To determine a standardised effort value for the prawn/scallop fleet equivalent to the effort of the scallop fleet, the catch of the prawn/scallop fleet was divided by the CPUE of the scallop fleet. Total effort was calculated as the sum of the effort of the scallop fleet and the standardised effort of the prawn/scallop fleet.

Surveys of scallop abundance have been conducted in November each year since 1983, at the end of the scallop and prawn fishing seasons and near the end of the breeding season, using the 20m twin-rigged research vessel 'Flinders'. A standardised pattern of survey trawls is carried out, using twin 50mm mesh trawls of 22.0m (12fm) total head rope length, to determine the abundance of scallops in the areas of the bay where the fishery operates. Scallops caught in

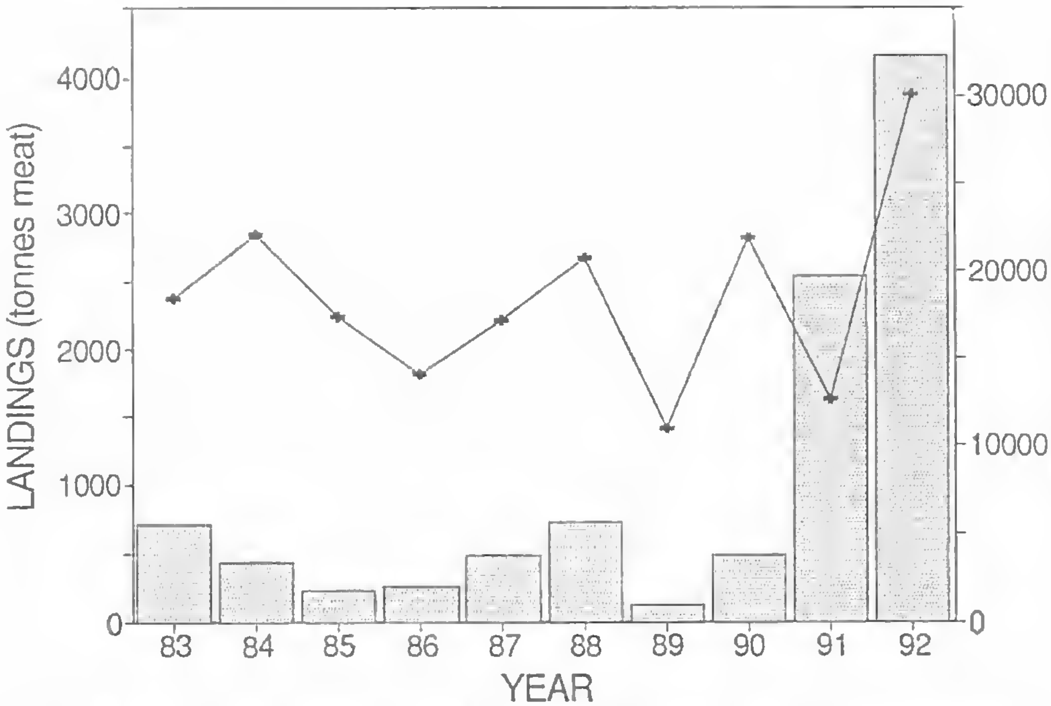

FIG. 1.Scallop catchs (tonnes meat) from Shark Bay,1983–1992 (stippled bars) and estimated total effort (+).

each survey trawl are separated, primarily on the basis of size, into recruits (0+ animals derived from the breeding season commenced in April that year (Joll,1987)) and residuals (1+ and older animals) and the numbers of each category recorded. Most recruits are less than 75 mm in most years and most residuals are larger than 75mm. However, when size overlaps occur, the recruits and residuals can still be separated on the pattern of the daily growth rings on the coloured left valve (Joll, 1988), with recruits showing widely spaced rings over the whole surface of the left valve while residuals have a zone of highly compacted rings near the valve margin.

Survey trawls are normally of 20 minutes duration and c.1 nautical mile long, although in areas of high abundance shorter trawl durations and distances are used. The distance covered by each survey trawl is determined either by radar fixes (1983–1989) or from global positioning system readings (1990 onwards) and, using the time taken for the trawl, the average speed of the trawl is determined. Catches of scallops are adjusted to catches per nautical mile, while the effect of speed on catchability is partially compensated for by applying factors determined by Penn (unpub.) for the catchability of adult (=residual-size) scallops relative to an arbitrary speed of 3.4kt. Survey data for each trawl shot are ultimately expressed as the catch of scallops per nautical mile (spnm) at 3.4kt for 12fm of head rope. The adjustment for the effect of speed on catchability does not compensate for the differences in catchability of recruit and residual-sized scallops and the indices for these two categories cannot be compared directly. However, the data allow for year-to-year comparisons within the categories.

Abundance indices of scallops on the main grounds (Shark Bay N of 25° 30'S) and the smaller ground in Denham Sound are derived from survey data as the mean abundance of recruits and residuals in the survey shots. The main grounds are further sub-divided into northern (N of 25° 10'S) and southern (S of 25° 10'S) sub-areas. Because the main grounds have contributed the bulk of the catch in most years, previous work (Joll & Caputi, in press) has concentrated on the relationship between an environmental factor (Leeuwin Current strength) and the index of abundance of recruits on the main grounds. The survey data have also been used to examine the relationship between index of abundance of recruits and residuals on the main grounds and catch from these grounds in the following year. However, recruitment in 1990 also gave rise to a significant catch from the

TABLE 1. Abundance indices of scallops from various sub-areas in Shark Bay from surveys in November 1983–92 (data are spnm for 12 ftm of net towed at 3.4 kts).REC.=recruits; RES.=residuals.

	MAIN GROUNDS				DENHAM SD.	
	N. AREA		S. AREA			
	Rec.	Res.	Rec.	Res.	Rec.	Res.
1983	47	237	32	301	65	158
1984	54	73	81	7	33	0.1
1985	134	91	247	2	30	0.5
1986	277	47	75	0.3	51	0.7
1987	598	133	609	35	32	7
1988	18	132	58	49	12	2
1989	97	45	19	2	32	1
1990	608	77	3756	73	631	21
1991	169	2411	50	4253	100	683
1992	162	770	157	467	761	439

Denham Sound grounds and data relating Leeuwin Current strength to recruit abundance and catch on the Denham Sound grounds are also presented.

Strength of the Leeuwin Current, flowing S along the Western Australian coast during the austral winter, is reflected in coastal sea levels (Reid & Mantyla,1976; Pearce & Phillips, 1988). The major spawning activity of *A. balloti* in Shark Bay occurs between April and July (Joll & Caputi, in press) and it is the strength of the current in these months which is most relevant. Unfortunately, sea level data are not available for the Shark Bay area for all of the relevant period, but the available data shows that changes in sea level at Carnarvon (25°S, 114°E) are reflected in sea level data from Fremantle (32°S, 116°E) one month later (Joll & Caputi, in press). As an index of Leeuwin Current strength in the Shark Bay area in April to July, the mean value of the sea level at Fremantle, lagged one month (i.e. May to August), was used.

RESULTS

Catch and Effort

Total scallop catch from Shark Bay by all vessels licenced ranged from 121 tonnes to 731 tonnes between 1983–1990, with a mean of 432tonnes/year (Fig.1). Catches for 1991 and 1992 were 2,532 and 4,144 tonnes respectively. The increase in catch in 1991 occurred despite total effort being the second lowest on record, while catch per unit effort (CPUE) of the scallop fleet was the highest on record at 200.2 kg h^{-1}, more than 5 times higher than the previous highest CPUE. The low effort figure for the 1991 season was a consequence of processing limitations on the fishing vessels, with vessels only fishing for a few hours each day and spending the remainder of the day processing the catch. The effort in the 1992 season was the highest on record, partly as a result of a large increase in effort by the prawn/scallop fleet, but the CPUE of the scallop fleet of 137.9 kg h^{-1} was second only to the 1991 figure and nearly 4 times greater than the previous highest CPUE recorded.

Survey Data

There was a very high abundance of recruits in November 1990, with an exceptionally high abundance in the southern sub-area of the main grounds - over 6 times higher than any of the previous indices determined for any sub-area of Shark Bay (Table 1). Moreover, despite a high 1991 catch, residual scallops in November 1991 were exceptionally abundant in the southern sub-area and high in the other sub-areas. These high abundances of residual scallops came about because, unlike years in which recruitment was at a more normal level, the effort of the scallop and prawn/scallop fleets could not fully exploit the 1991 recruitment. Another very large catch was taken in 1992, based primarily on the residual scallops detected in the 1991 survey, which were derived from the 1990 recruitment. By November 1992 the abundance of residual scallops had decreased considerably, reflecting the impact of the fishing activities of the fleets in the 1992 season, when recruitment to the fishery was close to normal.

Recruitment levels for 1990, categorized into 3 abundance classes (Fig. 2A), show that recruitment was not uniform through the sub-areas. The principal area of recruitment was in the southern sub-area of the main grounds, with a core of very high abundance (5,000 spnm) surrounded by an area of relatively high abundance (1,000–4,999 spnm). Residual scallop abundance in the 1991 survey (Fig. 2B) reflected fairly closely the distribution of recruits in the 1990 survey, with the exception of a small area of high abundance of residual scallops in the northern area. The apparent emergence of this area of residual scallops in November 1992 may indicate that recruitment in the northern sub-area occurred slightly later and was not measured fully by the November 1991 survey.

The highest recorded catches (12fm net at 3.4kts) in the 1990 and 1991 surveys were 19,075

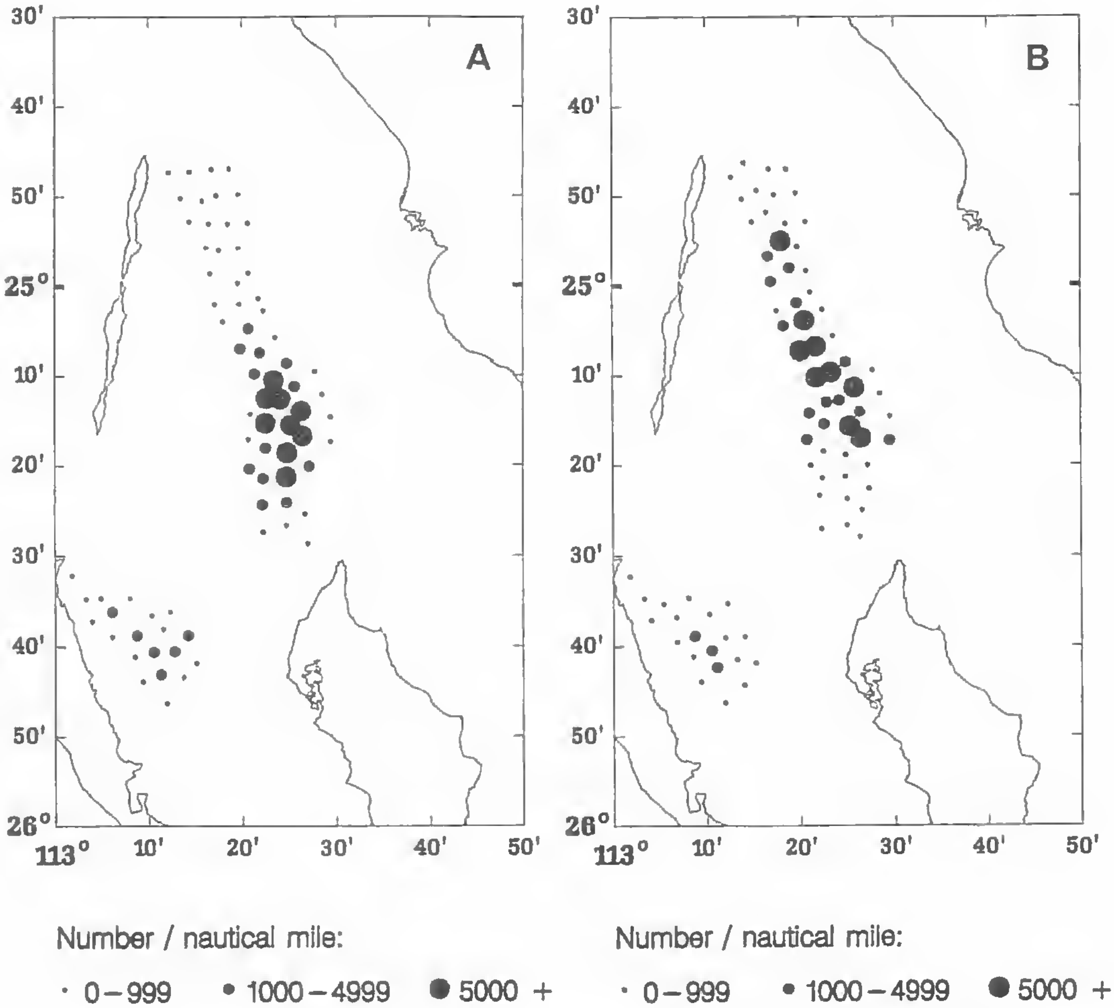

FIG. 2. Distribution of the abundance of scallops in Shark Bay recorded in surveys in November. A, Recruits, 1990. B, Residuals, 1991.

recruit spnm in 1990 and 59,242 residual spnm in 1991. Conversion of these catch rates to abundances requires application of catchability factors relevant to the various trawl speeds. Joll & Penn (1990) showed that the catchability of residual-size scallops at a speed of 2.5 kt is approximately 0.6, while the adjustment of this catchability factor to the higher trawl speed of 3.4kt at which the survey data are expressed is also 0.6 (Penn unpubl. data). Application of these catchability factors to the 1991 figure for the highest catch of residual scallops equates to an actual abundance of 164,561 spnm in the path of the trawl. Assuming a trawl path of 60% of the headrope length of trawl used (Joll & Penn, 1990), the area swept in a 1 nautical mile trawl would be 24,446 m^2. On this basis density of adult scallops in the shot with the highest abundance of residual scallops in the 1991 survey was estimated to be 6.7 scallops m^{-2}. The catchability of recruit scallops has not yet been formally determined. However, based on the lower swimming capacities of smaller scallops and the increased latency of their response to a stimulus to swim (Joll 1989b), it could be expected that the catchability of recruit-sized (50-60mm) scallops would be about 30-40% of that of residual-size scallops. On the basis that the catchability of recruit-size scallops is 40% of that

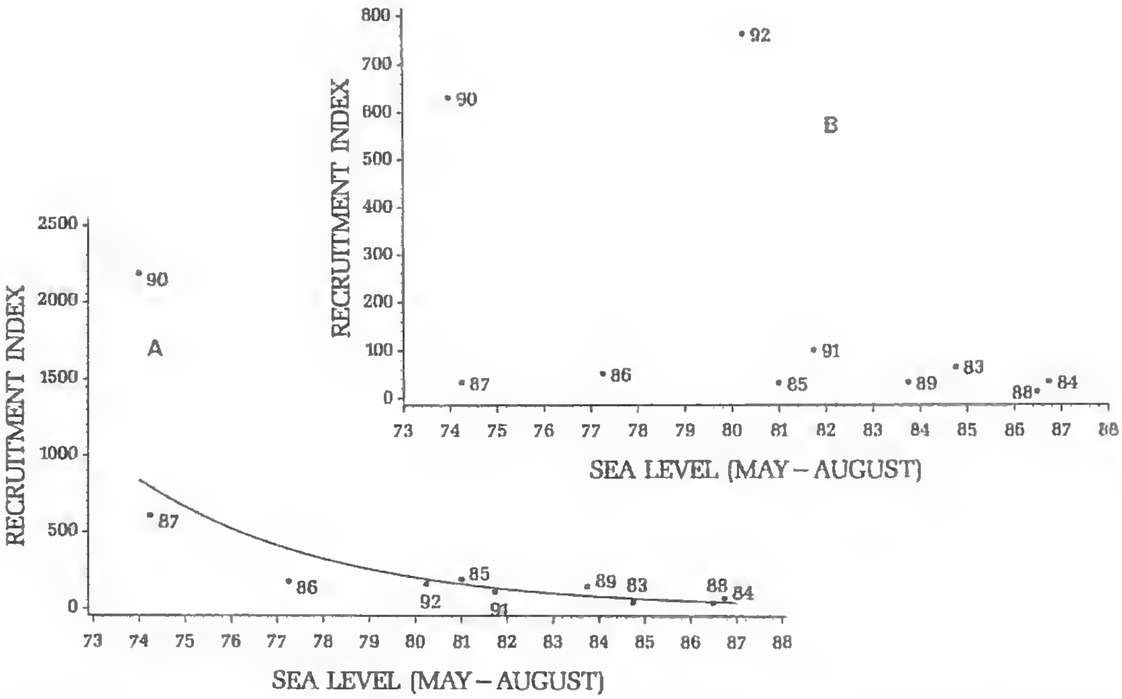

FIG. 3. Relationship between the index of recruit abundance (mean spnm) in Shark Bay and mean Fremantle sea level (cm) over the period May to August. A (bottom left), Main grounds. B, (upper right), Denham Sound.

of residual-size scallops, the density of recruit scallops in the path of the trawl with the highest catch of recruits in the 1991 survey was estimated at 5.4 scallops m^{-2}.

EFFECTS OF THE LEEUWIN CURRENT

The relationship between the recruitment index for the main grounds and mean Fremantle sea level over the period May to August in the period 1983 to 1992 (Fig. 3A) shows that the recruitment index was highest in years when the mean sea level was low. Recruitment data for Denham Sound (Fig. 3B) show a high recruitment index in 1990, when sea level was low. However, in 1987 when sea level was similarly low, there was no increase in recruitment and in 1992, when sea level was not particularly low, there was also a high recruitment.

In most years there is a high level of exploitation of the scallops recruiting to the fishery, which gives rise to a strong correlation between the abundance index of recruits in one year and catch on the main grounds in the following year and between sea-level in one year and catch on the main grounds the following year (Joll & Caputi, in press). However, because of the inability of the fleet to fully exploit the fishable stock available in 1991, there was a considerable carry-over of scallops into 1992. This gave rise to a high catch in 1992 on both the main grounds and the Denham Sound grounds which was not related to the sea- level of the immediately previous year (Fig. 4A,B). Although survey data showing recruitment strengths are not available prior to 1983, the inclusion of data for the 1983 catch and the 1982 sea level provide additional confirmation of a relationship between sea level and catch in the following year (except 1992) on both the main grounds and in Denham Sound.

DISCUSSION

The high 1990 recruitment led to massive 1991 and 1992 scallop catches. On a live weight basis, the 1992 catch of scallops was over 20,000 tonnes, making it the second largest single species fishery in Australia in that year after greenback jack mackerel. The combined catch of scallops by the scallop and prawn/scallop fleets in 1991 and 1992 was a little less than twice the accumulated catch of the previous eight years. The mean CPUE in 1991 was approximately 18 times greater than the highest mean CPUE in the Queensland saucer scallop fishery 1976-1987 (Dredge, 1988). Using an estimated mean adduc-

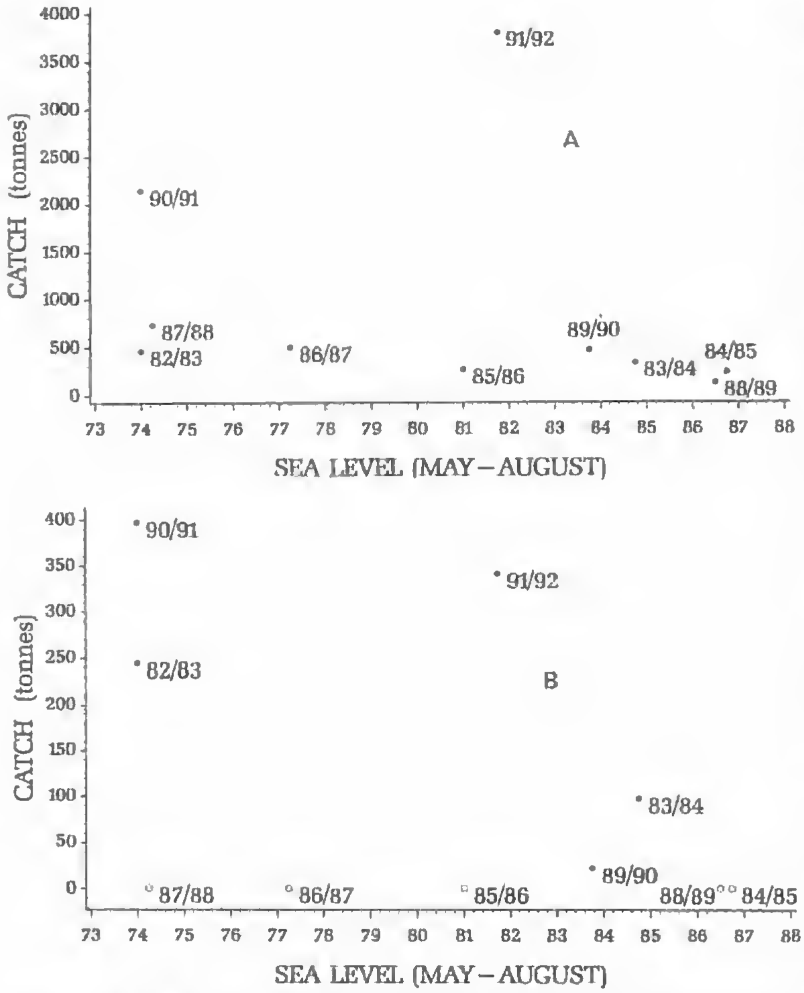

FIG. 4. Relationship between total catch (tonnes meat) and mean Fremantle sea level (cm) over the period May to August in the previous year. (86/87): (Year of sea level data/ Year of catch data). A (upper), Main grounds. B (lower), Denham Sound (open circles represent years of no effort in Denham Sound).

tor weight of 15g for scallops caught in 1991 and a mean of 20g for 1992, there were approximately 376 million scallops caught over 2 years. If most of these scallops had been caught in the year in which they recruited to the fishery, as is the case in years of more normal levels of recruitment (and without adjusting for the natural mortality of scallops from 1991 to 1992), an estimated catch of at least 5,500 tonnes would have been taken in 1991.

Estimated densities of scallops in the area of highest abundance in the 1990 and 1991 surveys were as high as 6.7 scallops m^{-2}. Higher densities of residual scallops than recruit scallops is probably a reflection of local variation in abundance, with slightly different areas trawled in different years. Alternatively, differences in catchability between recruit and residual-size scallops may have been underestimated, which would reduce the estimated density of recruits.

Based on the minimum value of the upper category of abundances (Fig.2), this figure equates (on the same basis as previous estimates) to densities of 0.57 residual scallops m^{-2} and 1.42 recruit scallops m^{-2}. Dredge (1988) noted maximum density of *Amusium balloti* in Queensland at around $1m^{-2}$, while Joll & Penn (1990) reported densities of scallops of $0.08\text{-}0.09m^{-2}$ in an area of Shark Bay in 1986. The area occupied by scallops at an estimated average minimum density of 1.42 recruits m^{-2} and 0.57 residuals m^{-2} in the 1990 and 1991 surveys (based on the area enclosed by shots of 5,000 spnm or greater) was around $90km^2$ and $60km^2$ in the two years respectively. Scallops at very high local densities and generally high densities across a wide area over a two year period indicate a capacity of the environment to support large numbers of scallops without any apparent depletion of the food resources.

The mechanism by which the Leeuwin Current affects recruitment success in Shark Bay is not fully understood. Satellite imagery shows that, when the Leeuwin Current is near the coast off Shark Bay, bodies of warm Leeuwin Current water sometimes move away from the main flow of the current and enter Shark Bay (Joll & Caputi, in press). This may flush larvae out of the bay or into the saline embayments along the mainland shore line. Hydrological flushing has been recognised as factor affecting recruitment in *Placopecten magellanicus* and *Pecten maximus* (Dickie,1955; Caddy,1979,1989; Thouzeau &

Lehay,1988). Alternatively, the higher temperature or lower nutrient levels of the Leeuwin Current water (Pearce,1991) may provide an environment which is less suitable for larvae.

The abundance pattern of 1990 (Fig. 2A) had a core of very high abundance surrounded by an area of relatively high abundance, suggesting that larvae were contained within a well-defined eddy feature at settlement. Dredge (1988) suggested that a gyre in Hervey Bay in Queensland may act to trap larvae of *A. balloti* and Caddy (1979) hypothesized that recruitment to the Bay of Fundy scallop fishery was positively influenced by the degree of retention of larvae within a gyre. Greater retention of larvae within Shark Bay, perhaps inside clearly defined hydrographic features, appears to be the most likely cause of increased larval survival and juvenile recruitment in years when the Leeuwin Current is weak.

The reason for disproportionately high recruitment in 1990, compared with that occurring at similar average sea level values in 1982 and 1987 is not clear. There may have been some additional hydrological factor which led to an unusually high level of larval retention within the bay or some other environmental event which led to a high retention or survival rate of larvae. The action of an additional favourable factor or factors within a low sea level environment already basically conducive to good larval survival may have been greatly heightened by the synchronisation of that event with spawning activity. *Amusium balloti* is a multiple spawner (Joll, 1987,1989a) with a larval life of c.22 days (Rose et al.,1988). With a relatively short larval life it may be that recruitment success can benefit from chance associations between spawning and short term environmental factors which are not reflected in the mean sea level. The very compact and unimodal size-frequency distribution of the 1990 recruits in the areas of very high abundance suggests that the bulk of the recruits in these areas were derived from one spawning. Synchronisation of an additional hydrological or other environmental event with a period of spawning may have led to the levels of recruitment success observed in 1990.

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